AN OVERVIEW OF THE ON-ORBIT CONTAMINATION OF THE LONG DURATION EXPOSURE FACILITY (LDEF)

W. K. Stuckey
The Aerospace Corporation
2350 East El Segundo Blvd.
El Segundo, CA 90245
Phone: 310/336-7389, FAX: 310/336-5846

SUMMARY

Contamination that leads to degradation of critical surfaces becomes a vital design issue for many spacecraft programs. One of the processes that must be considered is the on-orbit accumulation of contaminants. The Long Duration Exposure Facility (LDEF) has presented an opportunity to examine the deposits on surfaces returned from orbit in order to help in understanding the deposition processes and the current models used to predict spacecraft contamination levels. The results from various investigators on the contamination of LDEF have implications for material selection, contamination models, and contamination control plans for the design of future spacecraft.

INTRODUCTION

The control of contamination is very important for critical surfaces of satellite systems since contamination can lead to the degradation of optical or thermal properties. Contaminants can be accumulated during assembly, ground operations, launch, deployment, or flight, and all of these must be considered to control undesirable contaminant deposition on a spacecraft surface. Many investigations have addressed deposition mechanisms, predictive models, and measurements of contamination deposition under various conditions. However, LDEF represents the first opportunity for a laboratory examination of the contamination accumulated during nearly 6 years on orbit. This contamination represents the result of the combined environments experienced by LDEF in low Earth orbit. The characteristics of the deposits, their composition, and their effect on properties provide valuable information that will aid our understanding of the process of contaminant deposition on spacecraft surfaces. In this discussion, the contamination accumulated during the time LDEF was on orbit will be emphasized, rather than that occurring during assembly, ground operations, launch, etc., which can be studied by other means.

CONTAMINATION OBSERVATIONS

Contamination was immediately observable upon the retrieval of LDEF. Photographs were taken of the D9 tray from the M0003 experiment on the leading edge of LDEF while still in orbit. These photographs (ref. 1) clearly show debris on the D9 tray generated from atomic oxygen erosion of the Kapton from aluminized Kapton material. It is interesting that this debris had apparently migrated to adjacent areas while on orbit. Evidence for particulate migration was observed in other investigations of contamination after retrieval (ref. 2). The particulate contamination was reported to have been approximately Level 2000 on LDEF surfaces examined at the Kennedy Space Center (KSC). Most particulate contamination is not accumulated on orbit but comes from ground-based sources.

Molecular contamination was clearly evident in the initial observations of the LDEF vehicle upon return to KSC. There were multiple areas on LDEF having very heavy brown deposits (such as those on the space end of LDEF) that can be attributed to the outgassing from connectors. This kind of deposit would severely impact a critical component in the field of view of such a high outgassing source. Significant deposits were also observed on many other surfaces of LDEF (ref. 3). There were easily visible deposits associated with venting paths, particularly from the interior of the LDEF structure. The location of these deposits confirms the importance of the role of solar ultraviolet (UV) radiation and the photoenhanced deposition of contaminants, which was known to be important prior to the LDEF retrieval. Similarly, the ability of atomic oxygen to remove or alter contaminants was known. Deposits that were clearly associated with the atomic oxygen exposures were observed on many LDEF surfaces. Clearly, the selection of materials, the venting paths, the temperature, the UV interactions, and the atomic oxygen interactions are of utmost importance to control contamination and must be included in spacecraft design if a critical surface requires contamination control. Contamination control was not consistent on the LDEF experiments.

In addition to the visible deposits on LDEF, contamination was present on many surfaces not necessarily associated with line-of-sight deposition from an outgassing source(ref. 4). Infrared analyses identified this contamination as a mixture of silicones and hydrocarbons, with most contamination being typical of materials intentionally used on LDEF. This contamination, while not always sufficient for visible detection, is nevertheless significant for many optical components and has been an interference in many analyses of LDEF surfaces and studies of the impact residue in craters.

CONTAMINATION INVESTIGATIONS

Quartz-crystal microbalances (QCM's) were flown on the Long Duration Exposure Facility (LDEF M0003-14) by QCM Research, Laguna Beach, California, as contamination monitors. This subexperiment was one of 19 subexperiments that comprised the M0003 experiment assembled by The Aerospace Corporation. The QCM's used quartz crystals with two types of coatings. One set of leading- and trailing-edge QCM's consisted of crystals with 9,000 Å of aluminum and aluminum oxide (Al + Al_2-O_3) and a top layer of 150 Å of indium oxide (In_2-O_3). The second set of crystals on the leading and trailing edges consisted of 9,000 Å (Al + Al_2-O_3) and a top layer of 150 Å zinc sulfide (Zn-S). The crystals with the In_2-O_3 coating were selected for the on-orbit data acquisition. The QCM's consists of a pair of crystals, one that was exposed to the environment and termed the "sense" crystal, and one that remained unexposed and hence termed the "reference" crystal. The beat frequency monitored between the "sense" and "reference" crystal represents a change in mass of the "sense" crystal as a result of exposure, relative to the unexposed "reference" crystal.

The QCM response was recorded for about 14 months, the lifetime of the data acquisition batteries. The crystals continued to be exposed to the Low Earth Environment on Row 9 on the leading edge of LDEF and Row 3 on the trailing edge for the entire LDEF mission, even though the response was no longer recorded. Data were recorded in bursts lasting a period of 111.7 min (about one LDEF orbit). During this 111.7-min period, each data channel was scanned 32 times, producing a profile for the entire orbit. After the burst period, the data system rested for 93.16 h before start of the next burst period. Data were taken in this manner until the end of the recording media was reached, 424 days after launch. The maxima and minima frequencies were recorded for the leading- and trailing-edge QCM's during each period. The data corresponding to the minimal temperature during each orbit are shown in Figures 1 and 2 (ref. 5). Note that the trailing-edge QCM shows an increase in weight that continues for the entire 424-day data acquisition period, while the leading edge shows an apparent weight loss.

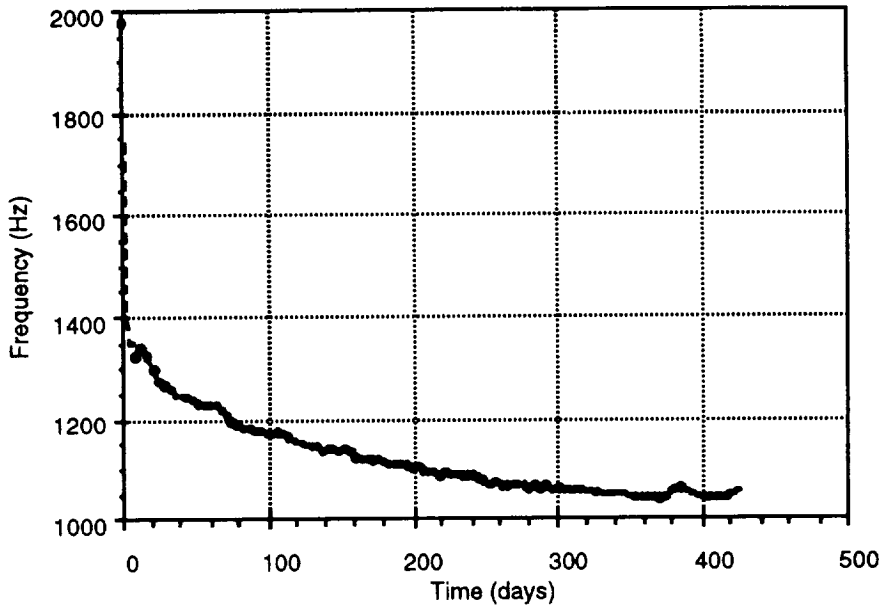

Figure 1. Leading-edge quartz-crystal microbalance frequency change.

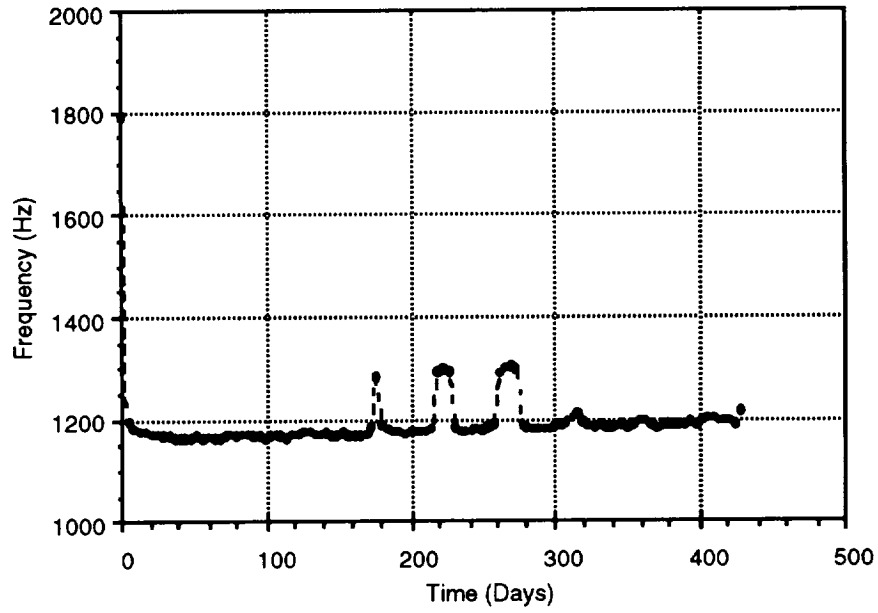

Figure 2. Trailing-edge quartz-crystal microbalance frequency change.

One of the most sensitive means to analyze material surfaces is by x-ray photoelectron spectroscopy. This technique probes ~50 to 100 Å at the surface and can reveal chemical information about the constituents. Both In_2-O_3 and Zn-S surfaces from the QCM's have been analyzed with similar results with respect to contamination (ref. 6). The data in Table 1 show that silicon is detected on both leading-edge and trailing-edge surfaces, with the silicon higher on the leading edge. The detection of substrate signals indicates an incomplete coverage or a coverage less than the electron escape depth (50 to 100 Å). Atomic oxygen erosion would explain the decrease in carbon species on the leading edge while the silicon would tend to form nonvolatile oxides and still be present. Note that the oxygen is also higher on the leading edge as expected. The trailing edge

shows higher levels of carbon and lower levels of silicon. These observations of differences between leading edge and trailing edge are confirmed by other analytical techniques. Results from the Secondary Ion Mass Spectrometry (SIMS) studies of the quartz crystals are shown in Table 2. About an order of magnitude higher level of silicon is detected for these crystals on the leading edge as compared to the trailing edge (ref. 5).

Silver Teflon samples have been studied from 11 of the 12 rows of samples around the perimeter of LDEF. The contamination of the Teflon surfaces varies according to the location on leading or trailing edge of LDEF. On the trailing edge, surface analysis shows that contaminants are present at levels similar to that found on the QCM surfaces discussed earlier. Some areas were more heavily contaminated with easily visible contaminants (ref. 7). However, on the leading edge, where erosion of ~1 mil of the Teflon has occurred, the Teflon surface is "clean," similar to representative control samples. Other eroded polymers were also found to have been cleaned (ref. 6). Since the contaminant films on LDEF typically contain silicon, which forms a nonvolatile oxide that should not be eroded, there appears to be a mechanical removal that accompanies the erosion of the polymers that results in a cleaning of the surface.

The accumulation of molecular contamination can increase solar absorptance. One of the experiments on M0003 was designed to measure the effects of contamination on material properties (ref. 8). Samples were placed on both the leading and trailing edges of LDEF in canisters where the samples were exposed for only 300 days during the first year on orbit and on the trays outside the canister where the samples were exposed for the entire mission. Results for the Si-O_2/Al second-surface mirrors in Table 3 show that some degradation in solar absorptance was observed on the samples with the 300-day exposure. The samples with the full 69-month exposure showed even further degradation. The degradation is slightly higher on the trailing edge in both cases. The x-ray photoelectron spectroscopy analysis of nickel mirrors in the same locations also indicates that the silicon contamination continued to accumulate after the first year in orbit. Note that for both the

Table 1. X-ray photoelectron spectroscopy analyses of quartz-crystal surfaces.

Sample	Surface Mole Percent (Normalized)						
	C	O	Si	In	Sn	Zn	S
In_2-O_3 Leading Edge	17	58	23	0.7	0.2	n.d.	0.1
Zn-S Leading Edge	48	35	10	n.d.	0.2	0.9	0.5
In_2-O_3 Trailing Edge	68	25	1.5	n.d.	0.3	n.d.	0.1
ZnS Trailing Edge	67	25	2.3	n.d.	0.4	0.1	0.1

(n.d. = not detected)

Table 2. Ion ratios on quartz-crystal surfaces detected by SIMS analysis.

Sample	Ion Ratios	
	Si^+/In^+	Si^+/Zn^+
In_2-O_3 Leading Edge	0.27	
In_2-O_3 Trailing Edge	0.036	
ZnS Leading Edge		63
ZnS Trailing Edge		6.8

leading-edge and trailing-edge specimens, the silicon levels are significantly higher for the full mission exposure compared to the 300-day exposure (see Table 4). The full mission exposures again indicate higher silicon levels on the leading edge. However, the 300-day exposure during the first year in orbit indicates a slightly higher level of silicon on the trailing edge. The carbon level is observed to be lower on both leading-edge samples where atomic oxygen has reduced the carbon level for the full mission exposure and for the 300-day exposure.

Table 3. Molecular contamination effects on Si-O_2/Al second surface mirrors.

Exposure		Solar Absorptance
Si-O_2/Al Lab Control		0.103
Si-O_2/Al Leading Edge	300 Days	0.107
Si-O_2/Al Leading Edge	Full Mission	0.112
Si-O_2/Al Trailing Edge	300 Days	0.113
Si-O_2/Al Trailing Edge	Full Mission	0.136

Table 4. X-ray photoelectron spectroscopy results on nickel mirror surfaces.

Sample		Surface Mole Percent (Normalized)							
		C	O	Si	Ni	F	Cl	S	P
Nickel Leading Edge	300 Days	19	43	2,5	34	1.7	0.2	0.1	0.3
Nickel Leading Edge Mission	Full	15	59	16	7.8	0.3	1.8	0.1	n.d.
Nickel Trailing Edge	300 Days	51	36	6.8	2.4	0.2	trace	0.1	2.9
Nickel Trailing Edge Mission	Full	40	43	12	n.d.	3.4	0.1	n.d.	n.d.

(n.d. = not detected)

CONTAMINATION LESSONS LEARNED

Contamination may degrade the optical and thermal properties of spacecraft materials. The effects on optical materials are documented in the LDEF literature and the Optical Materials Data Base. In fact, contamination is one of the dominant effects on optical materials on LDEF documented by other investigators. Contamination will increase the scatter of reflective optics and may decrease the transmission of filters and other external optics.

Surface analysis results have shown that the levels of contaminants such as silicon depend on the underlying material. For materials that have been eroded, the remaining material is contamination free. However, in nearby areas on materials that do not erode, the silicon is observed to remain in an oxidized form. Since the silicon is not expected to erode by chemical reaction, its absence on eroded material must indicate that a mechanical process is involved that results in a clean surface. The influence of UV radiation to enhance contaminant deposition is well known, and

contamination was observed on LDEF consistent with this mechanism. Most deposits were non-soluble and many heavier deposits were removed by physical means for analysis. However, some investigators have commented that the contaminants could be easily removed by solvent wipes of optical components.

The effects on the absorptance of solar energy are another type of concern. Contamination will increase the solar alpha and, as a consequence, the temperature of spacecraft surfaces. The degradation of second-surface mirrors is a good indication of an effect of contamination since the surface is expected to be stable to atomic oxygen and UV radiation. The observed degradation was less than 0.05 in solar alpha. This would generally be considered acceptable and is representative of cleaner satellites for which data is available (see Figure 3). Obviously, there are areas on LDEF with noticeable contamination where high values of solar alpha have been measured. These appear to be from localized sources that should be controlled to avoid undesirable increases in equilibrium temperatures.

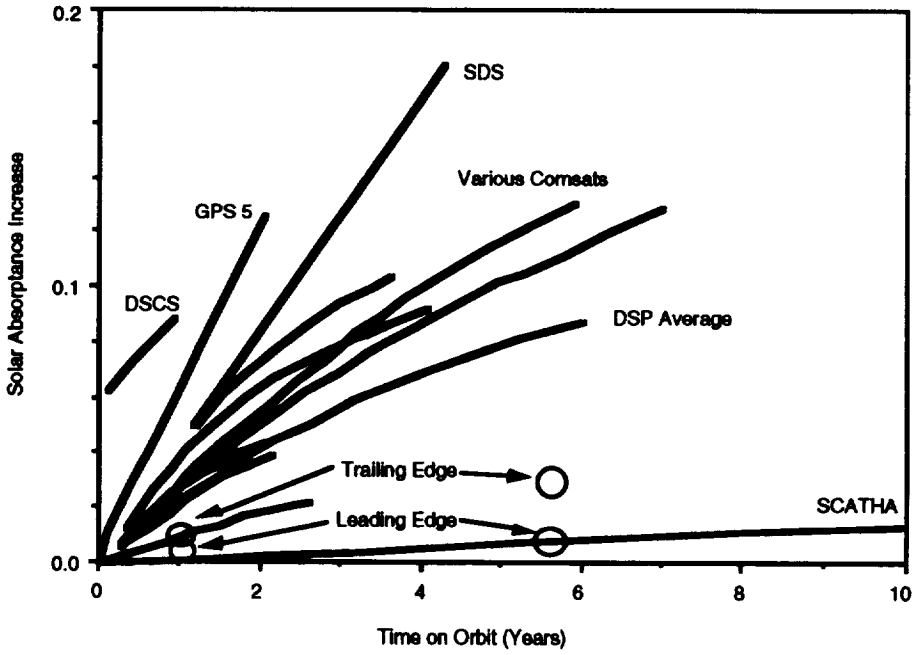

Figure 3. Fused-silica mirror degradation.

SUMMARY

There were many observations of contamination that occurred during the flight of LDEF. While the cleaner areas of LDEF had less than 100 Å of contaminant deposition, other areas were heavily contaminated. The most obvious include the large pieces of debris generated by atomic oxygen erosion that occurred while LDEF was still in orbit and the molecular deposits around tray vents from the LDEF interior or the trays themselves. The role of UV and atomic oxygen fixing of deposits on surfaces could be easily seen from the very noticeable brown stains attributed to atomic oxygen flow patterns or exposure to UV. The quartz-crystal microbalances show that the accumulation was still measurable after a year on orbit. The leading edge had higher contamination levels in some cases, apparently due to the return flux of contaminants. However, the atomic oxygen erosion could result in removal of the contaminants, leaving a "clean" surface. Silicones were known before the flight to result in oxidized, nonvolatile forms of deposits due to the removal of the hydrocarbon

portions of the silicones, but the high level of silicon is a concern for future spacecraft. A number of possible sources of silicones on LDEF have been suggested.

Examples of all of these various mechanisms affecting the level of contamination were observed on LDEF. The impact of the contamination depends on the material, its desired property, and the planned measurements. In order to minimize the impacts of contamination on a surface where the level of contamination is critical, contamination control plans and procedures should to be developed that cover all possible sources of contamination. The level of contamination may necessitate the establishment of contamination budgets or goals and the use of models for prediction of levels from outgassing sources, vents, and the return flux. Material selection is always a critical issue. A material that is acceptable by the ASTM E595 testing procedure does not necessarily eliminate contamination concerns or mean that it is not a potential contamination source. It only means that the material has a 1 percent or less total mass loss (TML) in 24 h at 125 °C and a 0.1 percent collected volatile condensable material (CVCM) at 25 °C. Similarly, a material that has been flown previously does not imply that it is not a potential contamination source. The acceptability of a material is dictated by its contamination potential and the requirements of each individual application.

REFERENCES

1. Meshishnek, M.J.; Gyetvay, S.R.; and Jaggers, C.H.: "Long Duration Exposure Facility Experiment Deintegration/Findings and Impacts." *LDEF-69 Months in Space First Post-Retrieval Symposium*, pp. 1073–1107, ed. Arlene S. Levine, NASA Conference Publication 3134, 1992.

2. Crutcher, E.R.: "Materials SIG Quantification and Characterization of Surface Contaminants." *LDEF-69 Months in Space First Post-Retrieval Symposium*, pp. 155-177, ed. Arlene S. Levine, NASA Conference Publication 3134, 1992.

3. Crutcher, E.R.; and Warner, K.J.: "Molecular Films Associated with LDEF." LDEF Materials Workshop '91, NASA Conference Publication 3162, 1992.

4. Stuckey, W.K.; Koontz, S.; and Crutcher, R.: "LDEF Contamination." *Proceedings of LDEF Materials Workshop '91*, pp. 689–698, ed. Bland A. Stein and Philip R. Young, NASA Conference Publication 3162, 1992.

5. Stuckey, W.K.; Radhakrishnan, G.; and Wallace, D.: "Post-Flight Analyses of the Crystals from the M0003-14 Quartz Crystal Microbalance Experiment." Second LDEF Post-Retrieval Symposium, San Diego, CA, June 4, 1992.

6. Hemminger, C.S.: "Surface Contamination on LDEF Exposed Materials." *Proceedings of LDEF Materials Workshop '91*, pp. 159–174, ed. Bland A. Stein and Philip R. Young, NASA Conference Publication 3162, 1992.

7. Pippin, G.L.; Hemminger, C.S.; and Stuckey, W.S.: "Performance of Silvered Teflon Thermal Control Blankets on Spacecraft." LDEF Materials Results for Spacecraft Applications Conference, NASA CP- , 1993.

8. Borson, E.N.; and Sinsheimer, F.B.: "Contamination Measurements on M0003." Second LDEF Post-Retrieval Symposium, San Diego, CA, June 4, 1992.